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Water Temperature in the Steamboat Drainage

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
FOREST SERVICE, U.S. DEPARTMENT OF AGRICULTURE
PORTLAND, OREGON

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This report results from the cooperative efforts of personnel from land management agencies and others interested in the aquatic environment of Steamboat Creek. Frank Moore, ardent steelhead fisherman and owner of Steamboat Inn, was instrumental in stimulating interest in the potential water temperature problem; Thomas Glazebrook, then Assistant Regional Forester (R-6) in charge of Watershed Management, suggested an intensive study; the following individuals participated in planning and execution of a team effort to gather and analyze the necessary data:

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Basic field data are on file with the Douglas County Water Resources Survey, at the courthouse in Roseburg, Oregon.

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WATER TEMPERATURE IN THE STEAMBOAT DRAINAGE

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FORESTS AND WATER TEMPERATURE

High quality water from our forest lands is subject to a rapidly increasing demand. Water from forested watersheds is suitable for many uses. One of the characteristics that determines water's usability, particularly for fish, is temperature.

The forests in the watershed of the Umpqua River are an important resource of the area. Steamboat Creek, one tributary of the North Fork of the Umpqua, is also an especially important spawning area for anadromous fish, particularly summer steelhead. In recent years, attention has been drawn to the potential impact of timber harvest on water temperature. Concern that increased water temperature in Steamboat Creek and its tributaries might influence the steelhead habitat prompted this cooperative[1/] study.

Fish may be directly affected by water temperature. Like all organisms, fish have a range of temperatures in which their growth and development is optimum. Fish also have limits to their tolerance of temperature and may die if these limits are exceeded. The absolute value for the optimum temperature and the lethal limit depends on the species. The important point is that temperature is a key determinant of how a given fish species will survive in a stream.

Temperature may affect a fish indirectly by affecting other things in its environment. The amount of oxygen dissolved in water is inversely proportional to water temperature. Populations of most of the fish pathogens strongly increase as temperature becomes warmer. Finally, temperature can affect the distribution of fish species. As temperatures increase, "warm water" species proliferate at the expense of "cold water" species.

Water temperature may also affect taste, odor, and color of streamwater. Under some conditions increased temperatures stimulate excessive production of algae, damaging the quality of water for human consumption, depleting the oxygen supply for aquatic organisms, and lowering the esthetic quality of streams.

The temperature of small forested streams can be greatly affected by man's logging activity in the surrounding forests. Man affects stream temperature by changing the amount of shade that protects the stream from the sun. Brown (1969) showed that removing the shade above a small forest stream increased the solar heat load by about six times. Shade removal, and not increased air temperature or soil temperature, was responsible for large temperature changes observed during that study.

The magnitude of the temperature change observed after logging along small streams has varied with the degree of stream exposure and the size of the stream. In North Carolina, Green (1950) compared stream temperatures of farmed and forested watersheds and found differences as high as 13° F. In the Pacific Northwest, Chapman (1962) checked comparable logged and unlogged drainages in Oregon's Alsea River Basin and found temperatures to be as much as 10° F. greater in logged areas where riparian vegetation was completely removed.

1/ *Cooperators in this study are listed on the inside of the cover.*

For a 250-acre patch-cut watershed on the H. J. Andrews Experimental Forest in the Oregon Cascades, Levno and Rothacher (1967) found no statistical evidence of a change in maximum water temperature at the mouth of the main drainage, following logging and burning of 25 percent of the area. However, two of the three clearcut units were high up on the slope with only limited stretches of perennial streamflow. The third included a 1,300-foot stretch of the main channel which was still partially shaded by shrubs and alders. No measurement of changes in stream temperature within the clearcut unit was made at this time. Two years later, the 1964 floods scoured the main stream channel to bedrock and removed all streamside vegetation. The following summer Brown and Krygier (1967) found increases of as much as 16° F. from the time the water entered the clearcut at the upper edge of the unit until it left the area at the lower end, a distance of 1,300 feet exposed to direct solar radiation.

On another 237-acre watershed in the same area, no measurable increase was found at the gaging station at the lower end of the drainage as logging progressed along the upper slopes. After 100 percent of the drainage had been clearcut, but with slash and understory vegetation providing partial stream shade, maximum water temperatures showed an increase of approximately 4° F. After the entire drainage was burned in the fall of 1966 and approximately 2,000 feet of the stream channel was cleared of debris, maximum recorded temperature exceeded that of the adjacent unlogged watershed by 12° F.

Brown and Krygier (1970) reported an increase of 14° F. in monthly mean maximum temperatures after complete exposure of a small stream in Oregon's Coast Ranges. Annual maxima rose 28° F. on this small stream where discharge drops to 0.01 c.f.s. (cubic feet per second) in late summer. Temperatures declined as vegetation returned.

OBJECTIVES OF THIS STUDY

The principal objective of this study was to provide forest managers in the Steamboat Creek watershed with data that would help them make decisions about logging and its impact on water temperature. Because logging operations in Steamboat Creek are typical of much of the area on the west slopes of the Cascade Range, the results should be representative of temperature changes elsewhere although ranges may differ due to latitude and elevation differences. A second objective was measurement of the effectiveness of varying densities and types of streamside vegetation for temperature control. Another was to provide a field check of temperature prediction models.

The study has been deliberately limited to measurement of temperatures as they exist today in the Steamboat drainage. The Bureau of Land Management and the Oregon State Game Commission are cooperating in other long-term studies in the area including (1) the effects of restoration measures on stream temperatures in Pass Creek, (2) postlogging stream temperatures in Francis Creek, and (3) the effects on the Francis Creek fishery.

THE STUDY AREA

Steamboat Creek, located on the west slopes of the Oregon Cascades drains 227 square miles and flows into the North Umpqua River 39 miles northeast of Roseburg (fig. 1). Steamboat

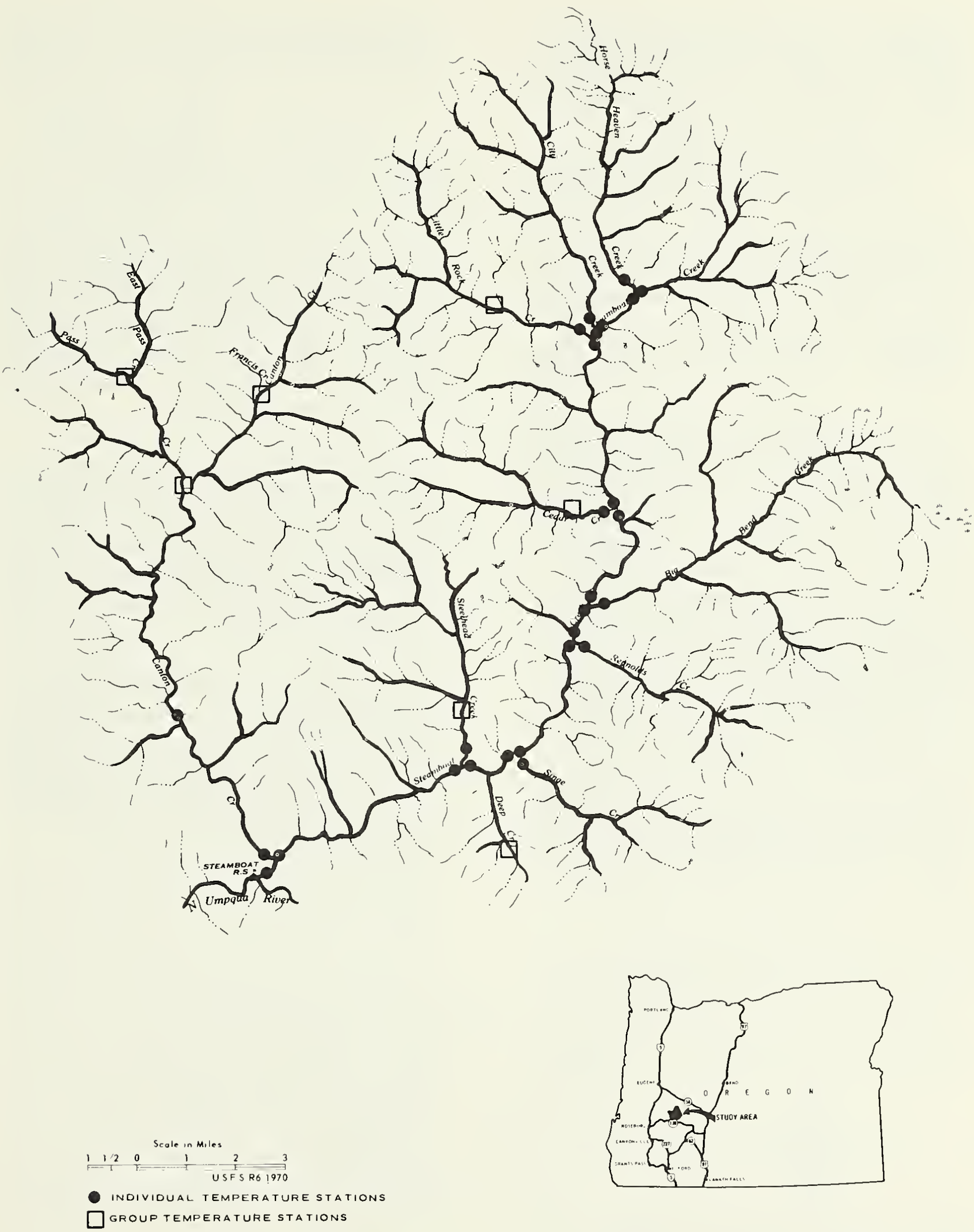


Figure 1.--Water temperature study area, Steamboat Creek drainage.

Creek and its tributaries are important spawning areas for anadromous fish, particularly summer steelhead; consequently, the entire drainage has been closed to fishing since 1932.

The Forest Service and Bureau of Land Management manage 81 percent and 12 percent, respectively, of the land in the Steamboat Creek drainage for a total of 93 percent under Federal jurisdiction. The remaining 7 percent is in private ownership, primarily in the Canton Creek drainage.

Most of the drainage has a cover of old-growth Douglas-fir. Road and logging development began in the drainage in 1955 and has expanded rapidly. Approximately 20,200 acres have been logged with a road system which extends up Canton and Steamboat Creeks and into the watersheds of most of the major tributaries. An estimated 35-50 miles of the 325 miles of live stream have been partially exposed during this period. Some sections of exposed stream are already shaded by regrowth of vegetation.

Summers are generally hot and dry. The bulk of the precipitation occurs from November through April. Precipitation at the Steamboat Ranger Station averages about 55 inches per year.

Topography is generally rough and mountainous with elevations ranging from 1,100 feet to 5,933 feet.

Flashy runoff and low base flow are characteristic of Steamboat Creek. Maximum recorded discharge is 51,000 c.f.s.; minimum recorded flow, 31 c.f.s. Peak flows generally occur between November and March; low flows generally occur in September and October.

The summer of 1969 was about average. Although there were many hot days, no air temperatures over 100° F. were recorded. Unusually heavy rains occurred in the last week of June. The rest of the summer was dry and warm until mid-September.

An unusually large snowpack in the previous winter contributed to high streamflow early in the summer. Streamflows were above normal in July but near normal later in the summer. A comparison with the four previous summers showed the following:

	Monthly minimum flow (c.f.s.)		
Year	*July*	*August*	*September*
1965	52	46	37
1966	46	34	34
1967	56	39	36
1968	47	42	50
1969 (study period)	78	50	43

STUDY RESULTS

Influence of Tributaries on Temperature of Steamboat Creek

The main stem of Steamboat Creek is important as a rearing area for small steelhead and a holding area for adults during the summer months. The objectives of this portion of the study were to determine what effect each tributary has on the temperature of Steamboat Creek and what temperature variations occur throughout its length.

Seventeen thermographs were installed in the main stem of Steamboat Creek above and below all major tributaries. These were continuous recording-type thermographs of various makes. Nine maximum-minimum thermographs were installed in each of the major tributaries just above their confluence with Steamboat Creek. All thermographs measured temperature to the nearest degree, and periodic checks were made for uniformity of accuracy. Streamflow measurements were made in these tributaries and in the main stem.

Maximum water temperatures occurred on July 27, 1969, and varied on the main stem of Steamboat Creek from 70° F. to 78° F. while major tributaries varied from 64° F. to 77° F. (fig. 2). Had July streamflow not been above normal, higher temperatures would be expected since maximums of 81° F. to 85° F. were measured in 1968. Even in the late 1950's prior to extensive development of roads and logging, stream temperatures of 75° F. were recorded in the main stem of Steamboat Creek and some tributaries.

Monthly averages of maximum temperatures for the 17 stations on Steamboat Creek ranged from 64° F. to 72° F. Monthly averages of the minimums ranged from 55° F. to 64° F. Monthly averages of diurnal fluctuations ranged from 6° to 12° F. Minimum temperatures occurred between 7 a.m. and 9 a.m. and maximum temperatures, between 2:30 p.m. and 4:30 p.m. Pacific standard time.

Most of the large temperature increases in Steamboat Creek occur within the main stream and not because of warm tributaries. The largest increase, between Little Rock and Cedar Creeks, is 5° F. Steamboat Creek flows south in this section and is exposed to the sun during midday. The stream is too wide to be shaded by streamside vegetation. A similar situation exists further downstream between Reynolds Creek and Singe Creek.

Big Bend Creek's cool water significantly reduced the temperature in Steamboat Creek. Main stem temperature dropped from 75° F. to 70° F. when Big Bend Creek's 64° F. water entered.

Canton Creek, the second largest tributary, did not influence the temperature of Steamboat Creek. Most of the large temperature increases in Canton Creek also occur in the main stream.

How can we judge or predict what the impact of tributaries will be on a stream like Steamboat Creek? The easiest way is with a mixing ratio which weights the contribution of each tributary by its discharge. Such a ratio can be written

$$\text{Adjusted temperature} = \frac{Dm\ Tm + Dt\ Tt}{Dm + Dt}. \qquad (1)$$

The adjusted temperature is the temperature of the main stem after the tributary enters; Dm and Dt are the discharges of the main stem and tributary; and Tm and Tt are the temperatures of the main stem

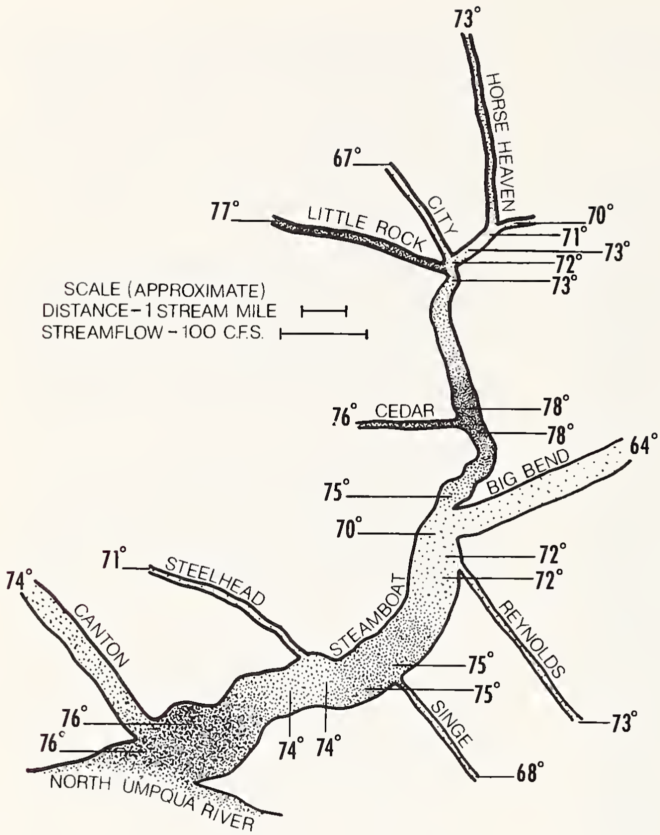


Figure 2.--Maximum water temperatures (degrees F.) on Steamboat Creek and tributaries, July 27, 1969.

and tributary. This enables prediction of the temperature a tributary must reach before the main stem temperature increases or decreases to a given value. An example is given in table 1 for Steamboat Creek tributaries.

Equation 1 tells us that since the impact of a tributary is proportional to its discharge, small tributaries must have much higher temperatures before they influence a larger main stream. This is borne out in table 1. The tributaries furthest upstream have the highest potential effects, since these tributaries contributed a larger percentage to the flow of Steamboat Creek at the point of confluence. For example, the flow rate of Singe Creek and City Creek on July 27 were nearly identical (2.5 c.f.s. and 2.3 c.f.s., respectively). If the temperature of City Creek were 6° F. greater than Steamboat Creek, we would expect a 1° F. increase in Steamboat Creek. Singe Creek, located further downstream where Steamboat Creek is much larger, must be 23° F. warmer in order to increase the main stem's temperature 1° F.

The accuracy of equation 1 can be checked using the measured temperatures shown in figure 2 and the measured discharges in table 1. Combining upstream discharge and temperature with tributary discharge and temperature produces approximately the measured downstream temperature below each tributary.

Table 1.--*Effectiveness of Steamboat Creek tributaries in changing the temperature of Steamboat Creek*

Tributary	Tributary discharge, July 27	Steamboat Creek discharge, July 27[1]	Percent of Steamboat Creek discharge[1]	Temperature increase necessary to change Steamboat Creek 1° F.
	----------*C.f.s.*----------			*Degrees F.*
Horse Heaven Creek	7.3	5.0	146	1.7
City Creek	2.3	12.3	19	6.3
Little Rock Creek	3.0	14.6	21	5.9
Cedar Creek	2.2	17.6	12	9.0
Big Bend Creek	31.6	19.8	160	1.6
Reynolds Creek	3.7	51.4	7	14.9
Singe Creek	2.5	55.1	5	23.0
Steelhead Creek	5.0	57.6	9	12.5
Canton Creek	25.1	62.6	40	3.5

[1] Above confluence of Steamboat Creek and tributary.

Management implications.--This technique of predicting the downstream impact of a tributary has many management implications. Which streams have the greatest potential impact on temperature both positively and negatively? Where should temperature control operations be concentrated? What are the expected cumulative effects of changes in many tributaries? These are but a few of the questions which can be answered quickly using this technique.

Impact of Logging on Temperatures in Tributaries of Steamboat Creek

Assessing the downstream impact of a tributary is important. Equally important, however, is assessing whether water temperature changes will occur within the tributary as a result of logging. The small tributary often forms the backbone of an anadromous fishery. In Oregon, these small streams provide the majority of the spawning and rearing sites for the fry. Thus, onsite impacts are just as important as downstream impacts. The objective of this portion of the study was to catalog the impact of various degrees of shade removal on stream temperature. Study sites included situations with no streamside cutting, complete exposure of the stream by clearcutting, clearcutting with provision of an uncut area immediately downstream as with an alternate block system of harvest, and stream protection using a thin buffer strip (table 2).

No cutting.--This situation represents a "control" condition which provides a rough benchmark for judging the normal temperature patterns in small streams in the Steamboat Creek watershed. On three of the tributaries studied, water temperatures at the upstream end of the section represent *undisturbed* forest conditions. In the three streams, the

Table 2.--*Forest cover and maximum water temperatures in tributary streams, Umpqua National Forest*

Stream (tributary to)	Volume flow	Flow direction	Period of record	Forest cover	Distance	Maximum temperatures		
						Upstream	Downstream	Change
	---*C.f.s.*---				---*Feet*---	-----------*Degrees F.*---------		
Francis Creek (Canton Creek)	0.3-0.9	SE.	June 17-Sept. 30, 1969	Undisturbed for total distance.	9,980	58	59	+1
			July 15, 1970	Buffer strip, 55,000 bd. ft., 3 percent of volume of clearcut.	1,680	58	59	+1
Pass Creek (Canton Creek)	5.1-15.3	ESE.	June 17-Sept. 30, 1969	Undisturbed upstream; two clearcuts on south side separated by undisturbed area of 1,225 feet.	1,290	58	66	+8
		ESE.	July 29-Sept. 30, 1969	Below the two south side clearcuts; clearcut to north, uncut to south.	1,265	65	64	-1
Deep Creek (Steamboat Creek)	.05-.10	N.	July 29, 1969	Undisturbed for approximately 1,000 feet upstream; then clearcut unit; 60 percent slash coverage through 1968 clearcut; ground water inflow.	1,900	56	60	+4
			Aug. 16, 1969	Buffer strip below clearcut; 30 feet wide; dense understory effective shade.	375	60	59	±0
Zinc Creek (South Umpqua)	.2-.3	N.	Aug. 28-Sept. 12, 1969	Several clearcut units upstream, nearest about 1,000 feet; 1950 clearcut to west; 1965 clearcut to east; some shade.	2,200	57	65	+8
			Sept. 4-12, 1969	Uncut forest downstream from clearcuts provides effective shade; ground water inflow.	1,300	64	60	-4
Deep Cut Creek (Jackson Creek)	.04-.05	S.	Aug. 2-26, 1969	Nearest clearcut units upstream 1-1/2 miles on mainstream, 1/2 mile on East Fork; thin buffer 50 feet wide with dense streamside vegetation.	550	60	61	±0
			Aug. 2-26, 1969	Tractor stripped area; no vegetation.	150	61	74	+13
Steelhead Creek (Steamboat Creek)	2.3	SSW.	Aug. 26-Sept. 12, 1969	Undisturbed upstream; thin buffer 30-foot average width; old growth plus 5-year-old alder; very little shade.	1,200	62	65	+3
Little Rock Creek (Steamboat Creek)	1.0-1.9	E.-SE	July 11-Sept. 9, 1969	Several clearcuts upstream, nearest 2,000 feet above upstream point; clearcut with 5-year-old alder.	1,100	72	76	+4
			July 11-Sept. 9, 1969	Thin buffer below clearcut, average 47 feet wide; old-growth Douglas-fir; sparse understory.	2,150	76	76	±0
Cedar Creek (Steamboat Creek)	11.4-2.2	ESE.	July 26-Aug. 22, 1969	North Fork--40 percent logged above clearcut; bottom of large clearcut below junction of North and South Forks.	4,200	69	83	+14

highest maximum, 62° F., was recorded on Steelhead Creek which drains in a southwesterly direction. Francis Creek and Pass Creek, the other two undisturbed streams, flow southeasterly. Although higher maximums might be recorded during prolonged periods of hot weather, this variation is probably representative of undisturbed conditions on small forested streams. There is some indication that undisturbed north flowing streams tend to be cooler than south flowing streams, but there is insufficient evidence from this study to support this.

Clearcutting.--Complete exposure of streams, as expected, produced the greatest temperature increases. Temperatures were measured above and below a clearcut which exposed 1,100 feet of stream on Little Rock Creek. Water temperature increased from 72° to 76° F. in this reach. The high upstream temperature (72° F.) was the residual effect of several other clearcuts along the stream above the clearcut studied.

The highest absolute temperature--83° F.--was recorded downstream from a large clearcut on Cedar Creek.

A similar effect was noted in Zinc Creek. An even sharper increase occurred in a 150-foot stretch of Deep Cut Creek, which was completely cleared of vegetation during road construction. In this very small stream, direct exposure to the south resulted in a 13° F. increase from 61° to 74° F. The importance of even short sections of open stream on water temperatures was noticed in the slash-covered section of Deep Creek, another very small stream. A 4° F. increase was measured in a 60-foot fireline and skid trail across the streambed, 2° F. increase where another 30-foot fireline crossed the stream, and 4° F. increase in a 10-foot diameter sump. Cool 51° F. ground water inflow reduced total change through the 1,900-foot, slash-covered section to 4° F.

Clearcutting in alternate blocks.--Clearcutting in alternate blocks allows for gradual removal and replacement of shade along any one stream. The theory here is that the cooler, shaded environment will reduce the high water temperatures to some acceptable level. The cooling effect of shade was examined with two types of studies--one focusing on environmental processes, the second on empirical observation.

Cedar Creek was selected as the site for studying the influence of the shaded environment on heated streams. The measurement site was within an uncut block of timber just downstream from a large clearcut. Water temperature approached 80° F. each day of the study. An energy balance was used to assess the gains and losses in heat for the stream as it moved from the clearcut into the shade. Methods used in this study have been reported elsewhere (Brown 1969).

The energy balance for Cedar Creek is shown in figure 3. Global radiation, the energy received from the sun, is reduced considerably by the forest canopy. The net radiation represents the energy absorbed by the stream. Additional energy is gained from the surrounding air (convection). Some of this energy is dissipated by evaporation; most of the energy is stored, however. This means that the stream will not cool in this reach but continue to warm very slowly. For most temperature measuring devices, the apparent change in water temperature would be zero.

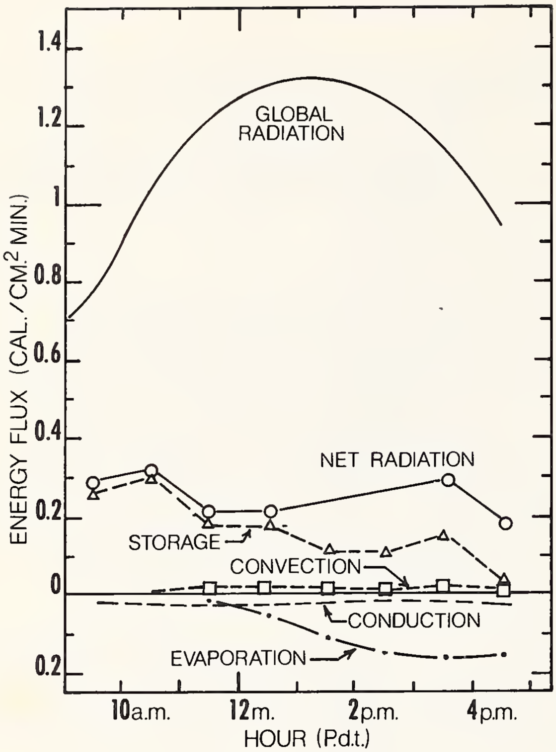


Figure 3.--An energy balance on a shaded reach of Cedar Creek during a clear day in July 1969.

Measurements of water temperature change in the 600-foot reach showed no significant reduction in temperature.

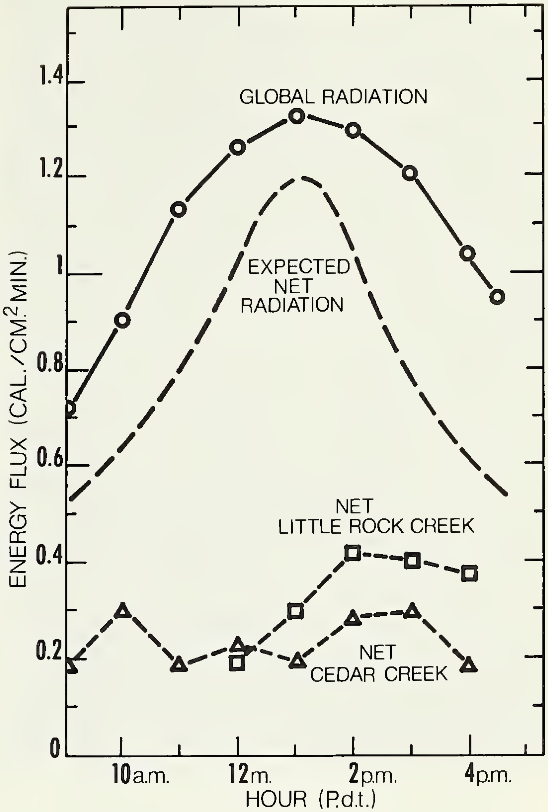
Measurements in shaded reaches of streams at various locations tend to support the "no change" conclusion from the study described above. Temperature changes in the shaded reaches of Francis Creek, Pass Creek, and Deep Creek are + 1° F., which is about the limit of precision for the instruments used (table 2).

Large temperature reductions, such as that measured on Zinc Creek (table 2), are generally the result of cold ground water entering the reach. Ground water temperatures average between 45° and 50° F.; it takes very little of this water to reduce surface water temperatures by 1° F. This is particularly true on small tributary streams. If, for example, a stream heated to 80° F. with a discharge of 1 c.f.s. has ground water inflow with a temperature of 45° F., equation 1 shows that only 1/34 c.f.s. (0.029) of this ground water will reduce the surface water temperature by 1° F. Such a small addition of water cannot be detected using normal current meter techniques.

Clearcutting with a buffer strip.--An excellent technique for controlling water temperature during logging is a buffer strip. Earlier studies (Brown 1969, Brown and Krygier 1970) indicated the importance of shade and the effectiveness of buffer strips in other areas for temperature control. The measurements reported above in areas of no cutting and in shaded areas below cutting units confirm this hypothesis. Again, two types of measurements were made to verify the effectiveness of buffer strips in the Steamboat Creek watershed.

A radiation balance was evaluated within a buffer strip on Little Rock Creek (fig. 4). This radiation balance

Figure 4.--Net all-wave radiation measured in a shaded reach of Cedar Creek and within a shaded buffer strip on Little Rock Creek during clear days in July 1969.



illustrates why even a thin buffer strip is effective in controlling temperature. The global radiation is the incoming solar radiation on the 2 clear days when the net radiation measurements were made. The "expected" net radiation is the portion of this incoming energy that would have been absorbed by the streams had no trees been present. This expected net radiation was greatly reduced by the streamside buffer strip on Little Rock Creek, almost as much as by the uncut block of timber bordering Cedar Creek. Such low levels of net radiation suggest that very little change would occur within the reach of Little Rock Creek protected by the buffer strip. The buffer strip on Little Rock Creek contained 75,000 board feet of timber, about 7 percent of the volume removed from the adjacent 55-acre clearcut.

Temperature measurements were made above and below the buffer strip on Little Rock Creek and the buffer strip left on Francis Creek. The temperature change in both instances was near zero (table 2). A 1,680-foot buffer strip on Francis Creek (fig. 5) contained only 55,000 board feet, 3 percent of the volume removed from the adjacent 29-acre clearcut. The effectiveness of this buffer strip was due, in large measure, to the excellent shade provided by understory vine maple. The understory remained intact as a result of careful felling and balloon yarding.

Management implications.--The studies of temperature and logging along the tributaries of Steamboat Creek provide forest-land managers with some important insights for temperature control.

Figure 5.--Balloon logging on Francis Creek clearcut area showing the buffer strip over the creek between the unit and the road. (Note balloon used for logging.)

Small streams shaded by forest vegetation tend to have temperature patterns with very little daily or seasonal fluctuation. In undisturbed streams daily variation in water temperature for a given stream may be less than between streams of different aspects. Complete exposure of a small stream by clearcutting can cause large changes in this temperature pattern. These conclusions support the conclusions of many earlier studies.

Forest-land managers can't count on shade to cool heated water. Where water temperature is critical, large temperature changes should be avoided in the first place. This can be achieved during logging by providing a buffer strip of vegetation that shades the stream. For small streams, understory species can provide shade as effectively as merchantable timber.

Predicting Temperature Change--A Field Check of Existing Models

A model for predicting temperature on small streams was described by Brown (1969) and later simplified for the special case of predicting the effect of clearcutting on stream temperature (Brown 1970). The purpose of this portion of the study was to check the accuracy of this simple model in the Steamboat Creek watershed and, if acceptable, use it to estimate the effectiveness of buffer strips for temperature control.

The simpler model for predicting the maximum change produced by clearcutting (Brown 1970) is:

$$\Delta T = \frac{A \times H}{D} \times 0.000267 \qquad (2)$$

where

ΔT = maximum change in stream temperature in degrees F. produced by completely exposing the stream,

A = surface area of the exposed section of stream in square feet,

H = maximum heat input varying with travel time and sun angle (available in Brown (1970)),

D = discharge, c.f.s.

The term H varies in the Steamboat Creek watershed from 4.0 to 4.5 B.t.u./ft.^{2}/min. The constant 0.000267 converts water from cubic feet per second to pounds per minute so that ΔT will be in degrees Fahrenheit. Predictions using this simple model are shown in table 3.

This table illustrates some of the shortcomings of this method as well as its potential value. The prediction on Pass Creek was within 3°-4° F. of the measured value. On this stream, the method was used to estimate the additive impact of two clearcuts separated by an uncut block of timber to the south (fig. 6). No adjustment was made for cooling in this portion, in accordance with findings reported earlier.

The prediction made for the clearcut in Little Rock Creek was much too high. Subsequent studies in 1970 revealed two possible sources of error. The first was an insufficient number of cross sections for estimating width. In 1969, measurements made at 100-foot intervals suggested that the average width was 16.8 feet. Discharge was 0.96 c.f.s. In 1970, measurements of width at 15-foot intervals suggested that the average width was 12.3 feet even though discharge was 1.11 c.f.s. Overestimation of width, and thus surface area, or underestimation of discharge will produce an overestimation of the maximum temperature change.

A second source of error in the prediction for Little Rock Creek was estimation of the value for the heat input, H. The simplified method assumes that all heat exchange can be accounted for by this term. Earlier work (Brown 1969) suggested that where streambeds were solid rock as on Little Rock Creek, significant amounts of energy would be absorbed by the bed. Energy budget measurements on Little Rock Creek in July 1970 confirmed this loss of heat. Roughly 17 percent of the net radiation was dissipated in this manner. Thus, the value for H should not be 4.1 but 3.4 B.t.u./ft.^{2}/min.

Combining these new measurements for a short stretch of Little Rock Creek, a prediction was made for the upper 640 feet of the area exposed by the clearcut. When an average width of 12.3 feet, discharge of 1.11 c.f.s., and a heat load of 3.4 B.t.u./ft.^{2}/min. was used, a predicted increase of 5.4° F. was obtained. The measured temperature increase was 4° F.

The predicted increase of 34° F. without the thin buffer strip on Little Rock Creek is too high (table 3). Problems with width estimation and heat flow into the streambed are applicable here also.

Table 3.--*Stream temperature increase predictions*

Stream and date of data	Forest cover	Exposed stream channel		Surface area	Discharge	Travel time		Sun angle	Predicted increase	Measured increase	Comments
		Length	Average width								
		------*Feet*-------		*Sq. ft.*	*C.f.s.*	*Hours*		*Degrees*	------*Degrees F.*------		
Steelhead Creek, Aug. 15, 1969	30 feet wide, thin buffer.	1,200	13.6	16,320	2.34	2/3	[1]4.2	61	8	4	Buffer about 50 percent effective.
Pass Creek, July 8, 1969	Alternate clearcut and leave on south side of stream.	1,386	12	16,632	2.06	1	[1]4.5	70	10	6-7	Appears reasonable.
Deep Cut Creek, Aug. 27, 1969	50 feet wide, thin buffer with dense understory.	550	4.4	2,420	.04	2	[1]4.1	57	74	±0	Unreasonable increase.
Little Rock Creek Aug. 21, 1969	Clearcut with 5-year-old alder.	1,100	16.8	18,480	.96	1-1/2	[1]4.1	59	21	6	Predicted value high.
1970[2]	Same	640	12.3	7,872	1.11		[1]3.4		5	4	
Aug. 21, 1969	Thin buffer, sparse understory.	2,150	14.4	30,960	.96	3	[1]4.0	59	34	6	Predicted value high.

[1] Values for maximum heat input varying with travel time and sun angle (*H*).
[2] Revised predictions.

The thin buffer on Steelhead Creek seems to be about 50 percent effective in preventing any temperature increase. This buffer contains an old-growth Douglas-fir overstory, average width, 30-foot, with a sparse understory of mixed hardwoods and conifers, especially at the lower end of the unit.

The predicted temperature increase on Deep Cut Creek is unreasonable. Problems in estimating all values in equation 2 become acute on such small streams. Discharge is difficult to measure, as is travel time for the average water molecule. Flow patterns in small pools become obscure, and minor amounts of ground water inflow can significantly decrease the water temperature. Accurate predictions from the simplified model may be impossible in such circumstances.

A final source of error implicit in the simplified method is its use for exceptionally long stretches of stream. Certainly, the capacity of a small stream for absorbing heat is not infinite. As stream temperature increases, more energy will be dissipated by convection and evaporation. As water temperature approaches air temperature, an equilibrium will be reached. This phenomenon is described in Edinger et al. (1968). For very long stretches, the simple method of estimating *H* by assuming that solar

Figure 6.--Pass Creek showing two clearcut units to the south (right) separated by an undisturbed strip. Temperature prediction made for the stream between points 1 and 2.

heat exchange represents total heat exchange is no longer applicable. Thus, the best results using this method will be obtained by using it on short, less than 2,000-foot, stretches of stream.

Management implications.--Predicting the effect of clearcutting on temperature can be a useful tool even with these limitations. With understanding of the principles illustrated by equation 2 and careful measurement of the important factors, accurate predictions can be obtained. The potential utility of the simplified method was illustrated on Pass Creek, on Little Rock Creek using better estimates of width and heat load, and on Steelhead Creek for judging the effectiveness of different densities of streamside vegetation.

Combined with equation 1, the prediction model allows the land manager to estimate onsite and downstream impacts. Where desirable, he can control the impacts, i.e., remove or leave sufficient cover so that maximum temperatures will not exceed a given amount.

RESULTS AND MANAGEMEMEMENT IMPLICATIONS

The results of this study generally are applicable to other forest areas as well as to the Steamboat Creek drainage.

The key to water temperature control is maintaining shade over the stream:

1. Small amounts of energy may penetrate a forest canopy, but normal temperature increases along shaded streams are small.

2. Differences in stream temperature due to natural causes may vary by 4° F. or more.

3. Removing all shade from a stream can increase water temperature 10° F. and more. A stream in one large clearcut had water temperatures of 83° F.

4. Shaded reaches downstream from a clearcut cannot be relied on to cool heated streams. Cooling that does occur can often be attributed primarily to inflow and mixing of cooler ground water.

Small streams are particularly sensitive to changes in shade:

1. For a given heat load and cross section, the change in temperature is inversely proportional to discharge--that is, the smaller the flow, the greater the temperature increase.

2. Exposing 150 feet of one small stream produced a temperature increase of 13° F.

Within a clearcut, water temperature may be controlled by leaving a buffer strip to provide shade. The key to planning buffer strips is recognizing that stream configuration determines buffer strip configuration:

1. Narrow streams may be shaded by brush.

2. Wide streams may require trees of sufficient height and density to effectively shade the stream.

3. When streamside shade is removed, and a relatively quick shade cover is desired, encouragement or propagation of cottonwood, alder, willows, and other fast growing species may shorten the time required to establish a buffer strip. Five-year-old natural regrowth of alder established after the 1964 flood is already providing some shade to small streams.

For any given stream, water temperature could be controlled by removal of shade over time so that temperatures would not exceed a target temperature in any one stretch or downstream.

The forest-land manager can predict water temperature changes that may result:

1. Equation 2 is a simplified method for predicting onsite changes.

2. Equation 1, used in combination with equation 2, can be used to predict downstream changes.

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Stream temperatures were studied in a drainage in which logging operations were typical of much of the commercial forests on the west slopes of the Cascade Range. Changes in water temperature of tributary streams influenced by various degrees of exposure from logging were measured, and a simplified prediction equation was tested.

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